

1 Comparison of particle number concentrations measured with AQ 2 Urban sensors in two different environments in Helsinki, Finland

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16 **Abstract.** The use of a diffusion charger based AQ Urban sensors to monitor particle number concentrations was
17 investigated in Helsinki metropolitan area. The comparisons between the AQ Urban sensors and traditional butanol CPCs
18 were made at a heavily trafficked street canyon (Traffic Supersite) and at an urban background site (UB Supersite) in
19 2022. The agreement with the measured particle number concentrations within different AQ Urban units was good.
20 Comparison of the AQ Urban sensor with the two CPCs showed that AQ Urban sensors should be suitable to measure
21 concentration of particles approx. larger than 10 nm in highly trafficked areas. The long-term agreement between AQ
22 Urban sensors and CPCs was also investigated in the two different environments between January 1st and August 15th,
23 2022. Overall, the correlation between AQ Urban sensors and the CPCs was good at both sites (r being 0.93 and 0.89,
24 respectively). The increased concentration of particles smaller than 10 nm and long-range transported pollution affected
25 the accuracy of AQ Urban sensors. Despite this downside of the method, the correlation between the AQ Urban sensor
26 and the CPCs was good during the whole measurement period, indicating that the sensor is well suitable for long-term
27 particle number concentration monitoring in urban environments in Finland. However, the observed effect of bi-modal
28 particle size distribution suggests that the performance of diffusion charger-based sensors may vary in different
29 geographic regions depending on the regional background concentrations of accumulation mode particles which should
30 be considered when applying the method in different locations.

31 1 Introduction

32 Exposures to particulate pollutants can cause serious health problems (Atkinson et al., 2014), and exposures to increased
33 levels of particulate pollutants have been estimated to cause 3.3 million premature deaths per year on the global scale
34 (Lelieveld et al., 2015). Fine particles ($< 2.5 \mu\text{m}$) can be transported deep into the human respiratory tract (Zanobetti et
35 al., 2014) and especially ultrafine particles ($D_p < 0.1 \mu\text{m}$) can enter even deeper into the respiratory tract (Schraufnagel,
36 2020). Especially in heavily trafficked environments, like street canyons, the concentration of ultrafine particles can
37 increase significantly causing adverse health effects (Pirjola et al., 2017; Rönkkö and Timonen, 2019; Trechera et al.,
38 2023). For example, Hänninen et al., (2025) suggested that ultrafine particles would be the most significant air pollutant
39 regarding premature deaths in Europe in 2023. In general, however, the health effects of ultrafine particles are not
40 completely understood yet (Vallabani et al., 2023).

41 The main anthropogenic sources of fine particle pollution in Helsinki metropolitan area are direct vehicular emissions,
42 road dust and residential wood burning (Aurela et al., 2015; Carbone et al., 2014; Järvi et al., 2008; Saarikoski et al.,
43 2008; Savadkoobi et al., 2023). In addition, long-range and regional transport increase the concentration of particulate
44 matter in Helsinki metropolitan area (Niemi et al., 2009, 2005, 2004). Secondary aerosol formation during transportation
45 increases the size of these particles e.g. (Harni et al., 2023). Particle number concentration (PNC) typically increases in
46 heavily trafficked areas in Helsinki metropolitan area e.g. morning and afternoon rush hours. Trapping of pollutants in
47 the boundary layer during cold days also increases PNC. In contrast to regional or long-range transported particles, the
48 increased PNC in heavily trafficked areas is connected to small particle size (Pirjola et al., 2017; Rönkkö et al., 2017).
49 The highest PNC in Helsinki Metropolitan area is typically measured near highways, heavily trafficked streets or at
50 airports (Lepistö et al., 2023).

51 Due to the harmful health effects of ultrafine particles, WHO has recommended the monitoring of PNC (WHO, 2021).
52 WHO also recommended that the minimum lower limit of particle size should be at least 10 nm for monitoring
53 measurements (WHO, 2021). According to Directive (EU) 2024/2881, PNC monitoring is regulated at rural and urban
54 background supersites and at “hotspot” sites with high ultrafine particle (UFP) concentrations. This same directive states
55 that the lower limit of the PNC measurements should be 10 nm, which corresponds to the lower particle size of the CEN
56 standard for outdoor butanol CPC measurements (EN 16976:2024).

57 Outdoor PNC measurements are typically performed using butanol CPC instruments which are widely used also in
58 laboratories. As PNC has typically high spatial and temporal variation, continuous measurements of PNC by utilizing a
59 wide measurement network could be beneficial especially in big cities. CPC measurements are costly (due to instrument
60 purchase and servicing), and maintaining the system is time-consuming, requiring regular maintenance and frequent
61 butanol refills. Due to the above reasons, the PNC monitoring networks based on CPCs are still quite rare. Measuring
62 devices based on diffusion charging could be useful if the coverage of indicative PNC measurements is wanted to be
63 increased. In earlier studies the PNC measured with diffusion-based instruments has been found to be in the range $\pm 50\%$
64 (Todea et al., 2017) and in the range $\pm 30\%$ (Asbach et al., 2024) when comparing to traditional butanol CPCs.

65 In Helsinki Metropolitan area, diffusion charger-based instruments, (AQ™ Urban sensors Pegasor Oy, Finland) are used
66 at eight measurement stations to continuously monitor PNC concentration. In addition, these sensors measure the lung-
67 deposited surface area (LDSA) concentration of particles e.g. (Kuula et al., 2020), Since the AQ Urban sensor
68 measurement technique differs from the traditionally used CPCs, we investigate the suitability of AQ Urban for PNC
69 measurements in different urban environments. In this paper we compare the PNC measured with the AQ Urban sensors
70 and CPCs at two sites in Helsinki metropolitan area during 7.5-month measurement period. In addition to this a
71 comparison measurement with seven AQ Urban sensors and two CPCs were made during 6-week measurement period.
72 The study aims to gain better understanding of the potential and challenges of AQ Urban, and diffusion charger-based
73 sensors in general, in long-term PNC monitoring.

74 2 Experimental

75 The 7.5-month measurement period was conducted at two sites in Helsinki Metropolitan area between January 1st and
76 August 15th, 2022. The measurement sites were Traffic Supersite and Urban Background Supersite (UB Supersite) in
77 Helsinki. PNC measured with the AQ Urban sensors were compared to those measured with the CPCs during the

78 measurement period at the two sites. In addition, a 6-week comparison measurement with 7 different AQ Urban sensors
79 were made at the Traffic Supersite between August 30th and September 19th, 2022.

80 The Traffic Supersite station is an urban measurement station operated by the Helsinki Region Environmental Services
81 Authority (HSY), located in a street canyon on the street Mäkelänkatu (60.19654° N, 24.95172° E) in Helsinki. The
82 Traffic Supersite station monitors continuously urban air quality with measurements of particulate and gaseous
83 components. The measurement station is markedly affected by motor vehicle emissions since it is a street canyon,
84 consisting of six lanes (Hietikko et al., 2018). More detailed descriptions of the site and its air flow patterns are found in
85 (Barreira et al., 2021; Hietikko et al., 2018; Kuuluvainen et al., 2018).

86 The Urban Background Supersite (UB Supersite, 60.20306° N, 24.96103° E) is the SMEAR III station located in Kumpula
87 campus area (Järvi et al., 2009). The effect of local traffic is quite low at the UB Supersite compared to the Traffic
88 Supersite because of the markedly longer distance to the main road (approximately 150 m from the station with a daily
89 traffic load of approximately 50 000 vehicles). The UB Supersite is affected by residential wood combustion during the
90 winter months (Järvi et al., 2008). At the UB Supersite particle physical and chemical properties and trace gases are
91 continuously measured.

92 PNC was measured at the Traffic Supersite and at the UB Supersite with diffusion charger-based AQ Urban (Pegasor,
93 Finland) sensors. At both sites the lower limit of particle size was adjusted to be 10 nm, while the larger particle detection
94 size of the instrument was ~600 nm. (Kuula et al., 2019; Rostedt et al., 2014). The AQ Urban sensor measures the escaping
95 current of charged particles. The measured escape current of the AQ Urban sensor closely matches the lung deposited
96 surface area of particles and is reported in addition to particle number. The AQ Urban sensor determines count median
97 diameter (CMD) indirectly by measuring the electrical current produced when particles are diffusion-charged. The
98 determination of CMD is based on the calibration of the instrument and the assumption that the aerosol size distribution
99 is lognormal. The instrument estimate the count median diameter (CMD) by continuously stepping between a low and
100 variable, high voltage settings; the median particle size is determined by the cutoff voltage of the half-maximum signal
101 compared to the low cutoff signal. Using this mean particle diameter and assuming a lognormal particle size distribution
102 with fixed standard deviation the instrument calculates the PNC (Janka and Saukko, 2017). The temperature of the AQ
103 Urban sensors was set to be 40 °C above the ambient temperature.

104 PNC was measured also with CPC instruments at both sites. At the Traffic Supersite the used CPC was an A20 (Airmodus
105 Ltd.) with a cut-size (D_{p50}) 5.4 nm and at the UB Supersite the used instrument was a CPC model 3756 (TSI) with a cut-
106 size (D_{p50}) 7 nm. A dilution was used before the CPC at the Traffic Supersite during the measurements to get reliable
107 results also during periods of high PNC at the site.

108 During two three-week periods between August 30th and October 10th, 2022, a total of seven AQ Urban sensors were
109 installed at the Traffic Supersite. One AQ Urban sensor was chosen as a reference instrument (Ref) since it was located
110 at the Traffic Supersite during the whole six-week period. In addition to the reference instrument six other AQ Urban
111 sensors were used (1–6). Three sensors during the first three weeks (1–3, August 30th – September 19th) and another three
112 during the last three weeks (4–6, September 19th – October 10th). During these periods PNC was measured also by using
113 two CPCs with different cut-sizes. The CPCs were an Airmodus A20 CPC with a cut-size 5.4 nm and an Airmodus A20

114 CPC with a cut-size 10 nm. A dilution was used for both CPCs at the Traffic Supersite during the six-week comparison
115 period.

116 Particle number size distribution was measured at both stations with a Differential Mobility Particle sizer (DMPS) using
117 a Vienna type Differential Mobility Analyzers. At the Traffic Supersite an Airmodus A20 model CPC was used in the
118 DMPS system and sample was dried using a silica gel dryer. At the UB Supersite the Twin DMPS had TSI model 3772
119 and 3756 CPCs with a 50 cm long Tropos Nafion dryer. At the Traffic Supersite the measured particle size range was
120 between ~10 and ~800 nm and at the UB Supersite it was between 3 and ~800 nm.

121 The accuracy of Airmodus A20 CPC is < 10 % up to PNC 30 000 p cm⁻³ and for the TSI 3756 CPC the accuracy is about
122 5 % when the total particle concentration is below 50 000 p cm⁻³ (based on the manufacturer information). The accuracy
123 of the DMPS-CPC system is about ±10 %. The changes in the instrument flow rates were mainly caused by the changes
124 in air pressure. The dilution at the Traffic Supersite was applied using a bridge dilution. The uncertainty of the bridge
125 diluter was determined to be 2 % in a laboratory test. . In long-term field measurements, however, the bridge diluter may
126 be prone to contamination, and, hence, the dilution ratio may not be constant throughout the measurements. This change
127 in the dilution ratio was determined after the measurement, and the measurement data was corrected using a moving
128 correction for the dilution. If estimating the propagation error using a maximum 10 % error for CPC and 10 % error for
129 the bridge diluter, the total uncertainty is around 15 %.

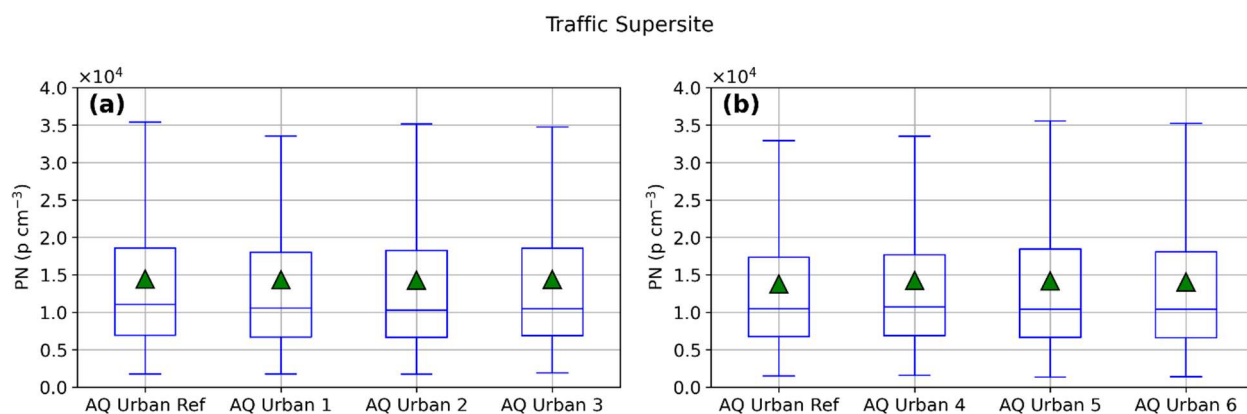
130 The flow rates of the CPCs were constantly checked, together with draining of butanol to avoid interference of condensed
131 water. For DMPS, the silica gel was changed regularly, and the flow rate was adjusted if the deviation was > 1 %. The
132 CPCs and DMPS-CPC systems were placed inside the measurement station, so the instruments were in stable condition
133 (e.g., temperature and relative humidity). Hence, it can be assumed that the temperature and relative humidity of the
134 samples entering the CPCs and DMPS-CPC were quite constant during the measurements. The AQ Urban sensors, on the
135 other hand, were placed outside the container, but their sample temperature was set to be 40 °C above the ambient
136 temperature, so especially RH should not have affected measured PNC. The effect of regional and long-range transport of
137 particulate matter to Helsinki metropolitan area can be seen by the elevated PM_{2.5} and BC concentrations measured at an
138 Rural background site located in Luukki (60.3143 °N, 24.6846° E). Luukki air quality measurement station is operated
139 by the HSY and is a Helsinki metropolitan area rural background station situated in clean background area 20 km from
140 the Traffic Supersite. At the Rural background site, no major local pollution sources are nearby and the increased
141 concentrations of PM_{2.5} and BC are mainly due to long range or regional transport of particulate matter. The concentrations
142 of PM_{2.5} and BC at Luukki measurement station were measured using the Fidas 200 (Palas GmbH) and Multi-Angle
143 Absorption Photometer (MAAP, Thermo Electron Corporation) instruments. The further discussion is based on hourly-
144 averaged data if not otherwise mentioned.

145 3 Results and Discussion

146 3.1 Comparison of particle number concentrations between AQ Urban sensors and CPCs

147 The boxplots of hourly-averaged PNC (particles cm⁻³) measured with the different AQ sensors during the two instrument
148 comparison periods are shown in Fig. 1. The outliers corresponding to high measured PNC are omitted from boxplots in
149 order to make their layout clearer. The linear regression between the PNC measured with different AQ Urban sensors (1-

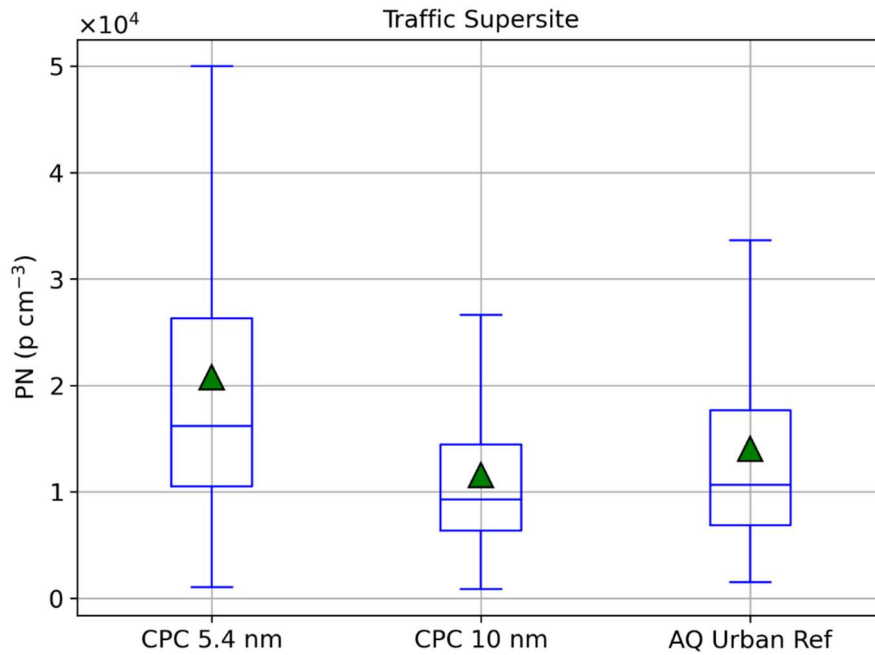
150 6) to the reference AQ Urban sensors are shown in Fig. S1. The Pearson correlation coefficient (r) is 0.99 for all other
 151 AQ Urban sensors except for AQ Urban sensor 4 which had slightly lower correlation coefficient ($r=0.97$). This is
 152 probably due to few outliers in the data set which can be seen in the correlation plot in Fig. S1d. The slope of the linear
 153 regression of the measured PNC between AQ Urban sensors against the reference AQ Urban sensor varied between 1.0
 154 and 1.06. The offset of the linear regression was negative or positive depending on the AQ Urban sensor, but it was low
 155 compared to the measured PNC. The agreement of PNC measured with different AQ Urban sensors can be concluded to
 156 be very good, which can be seen also from the time series in Fig. S2.



157

158 **Figure 1.** Comparison of hourly-averaged PNC measured with seven different AQ Urban sensors at the Traffic Supersite during the
 159 first (a) and second (b) 3-week comparison period. The median is the horizontal line within the box, and the green triangle is the mean
 160 value. The box spans from the first to the third quartile, and the whiskers extend to 1.5 times the interquartile range. The outliers
 161 corresponding to high PNC are not shown in the figure.

162 During the instrument comparison period, PNC were measured at the Traffic Supersite also with two Airmodus A20 CPCs
 163 having different cut-sizes of 5.4 nm and 10 nm (Fig. 2). The measured hourly-averaged PNC with the reference AQ
 164 Urban sensor agreed more closely to that measured with the CPC having a cut-off size of 10 nm compared to that having
 165 a cut-off size of 5.4 nm. This is expected since 10 nm is the lower estimated detection limit of the AQ Urban sensor. The
 166 correlation coefficients (r) between the measured PNC with the reference AQ Urban sensor and the CPCs having a cut-
 167 off diameter of 5.4 and 10 nm were 0.98 and 0.97 respectively (Figs. S3a and S3b). The slope of CPCs having cut-off
 168 diameters 5.4 and 10 nm respect to AQ Urban sensors were 1.36 and 0.73 respectively (Figs. S3a and S3b). The lower
 169 particle number concentrations measured with the AQ Urban compared to the CPC with the cut-off size 5.4 nm is due to
 170 the different lower detection limits of these two instruments. Especially in the vicinity of heavily trafficked streets the
 171 concentration of particles below 10 nm can expect to be high (e.g. Belkacem et al., 2020; Choi et al., 2014; Rönkkö and
 172 Timonen, 2019) and has been measured to be significant also at the Traffic Supersite (Hietikko et al., 2018; Teinilä et al.,
 173 2024). The lower slope of the linear regression with the CPC with cut-off size of 10 nm and to AQ Urban sensor detects
 174 the charge fraction of particles below 10 nm (Fig. S3c).

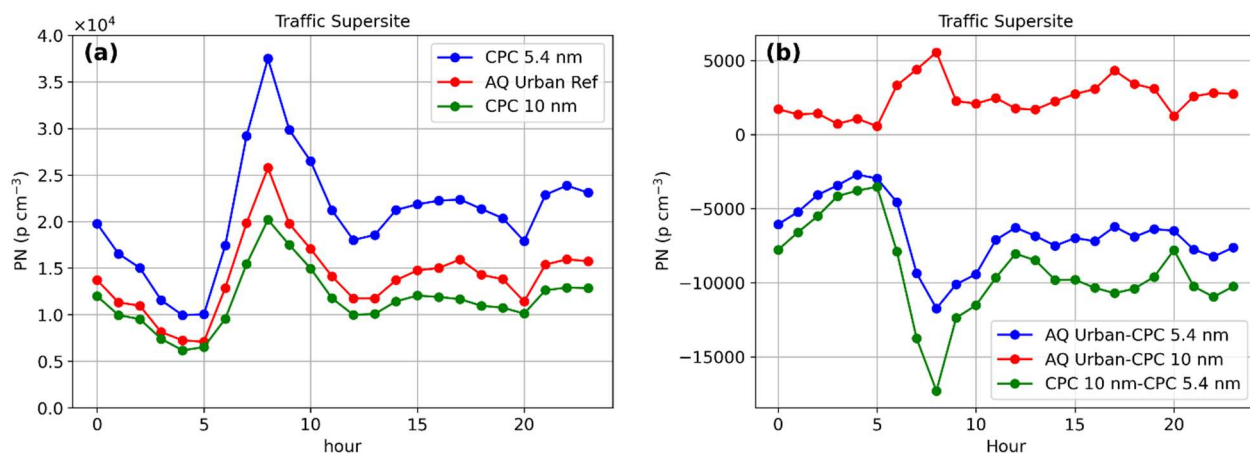


175

176 **Figure 2.** Comparison of hourly-averaged PNC measured with the reference AQ Urban sensor and two CPCs with different cut sizes
 177 at the Traffic Supersite during the 6-week period. The median is the horizontal line within the box, and the green triangle is the mean
 178 value. The box spans from the first to the third quartile, and the whiskers extend to 1.5 times the interquartile range. The outliers
 179 corresponding to high PNC are not shown in the figure.

180 The hourly diurnal variations of PNC measured with two CPCs with different cut sizes and the reference AQ Urban sensor
 181 during the comparison period are shown in Fig. 3a and the differences in the measured PNC in Fig. 3b. The diurnal
 182 patterns of the measured PNC with the different instruments are identical although the measured PNC are different
 183 showing that they all observe the contribution of traffic on the PNC Especially, during the morning rush hours, the PNC
 184 increased at the Traffic Supersite (Fig. 3a). The higher PNC during the morning rush hour was likely related to the more
 185 efficient dilution and mixing of pollutants during afternoon. Also, the lanes of traffic towards the city center were closer
 186 to the measurement station, which may emphasize the effects of morning rush hour when people are heading towards city
 187 centre. The evidence of the existence of particles below 10 nm can be seen when comparing the two CPCs during the rush
 188 hours. Also, the slope of the measured PNC between the CPC with cut-off size 5.4 nm with respect to the CPC with cut-
 189 off size 10 nm was 1.80 (Fig. S3c). The AQ Urban sensor measured higher PNC compared to the CPC with the cut-off
 190 size 10 nm during the rush hours. This result further supports the idea that the lower detection limit of AQ Urban sensor
 191 was less than 10 nm. However, it is also possible that the AQ Urban sensor estimated the count median diameter (CMD)
 192 erroneously (see the discussion in the next chapter).

193

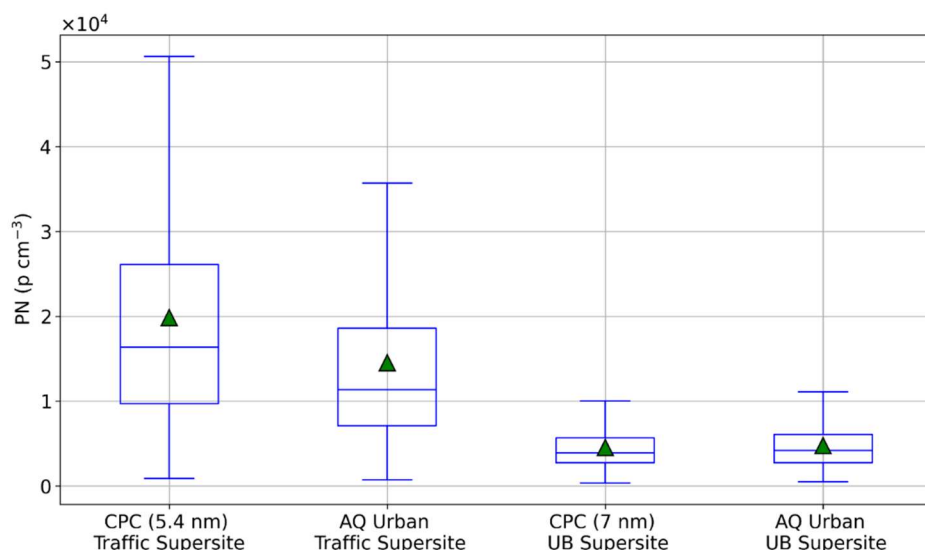


194

195 **Figure 3.** Hourly diurnal variation of the measured PNC (a) and the PNC difference (b) measured with two CPCs having different cut-
 196 size and the reference AQ Urban sensor during the 6-week comparison period at the Traffic Supersite.

197 **3.2 Particle number concentrations measured in two different environments in Helsinki**

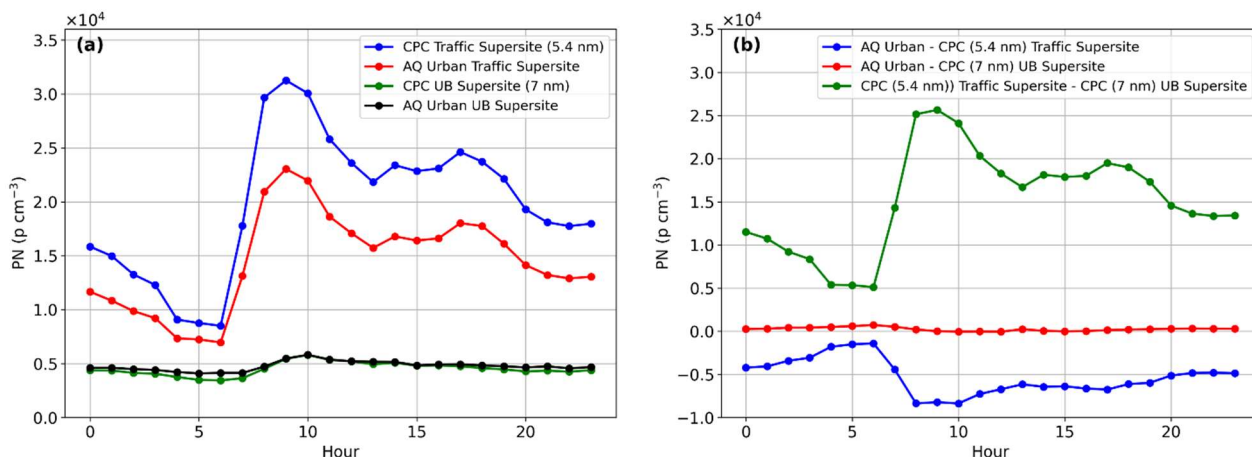
198 The PNC measured with the AQ Urban sensor and the CPCs in two different urban environments (Traffic Supersite and
 199 UB Supersite) were compared between January 1st and August 15th, 2022. At the UB Supersite the average PNC measured
 200 with the AQ Urban sensor was like that measured with the CPC having a cut-off size 7 nm (Fig. 4). At the Traffic Supersite
 201 the measured PNC with the AQ Urban sensor were lower compared to those measured with the CPC having a cut-off size
 202 5.4 nm which was observed also during the six-week comparison period.



203

204 **Figure 4.** Comparison of hourly-averaged PNC measured with the AQ Urban and CPCs at the Traffic Supersite and at the UB Supersite
 205 during the 7.5-month measurement period. The cut-off size of the CPC at the Urban traffic site was 5.4 nm and at the Urban background
 206 site 7 nm. The median is the horizontal line within the box, and the green triangle is the mean value. The box spans from the first to
 207 the third quartile, and the whiskers extend to 1.5 times the interquartile range. The outliers corresponding to measured high PNC are
 208 not shown in the figure.

209 The hourly diurnal variation of the PNC measured with the AQ Urban sensors and the CPCs at both sites are shown in
 210 Fig. 5a and the difference of the measured PNC between the AQ Urban sensors and the CPCs in Fig. 5b.



211
 212 **Figure 5.** Hourly diurnal variation of measured PNC at the Traffic Supersite and at the UB Supersite with the AQ Urban sensors and
 213 the CPCs (a) and the difference of the measured PNC (b) during the 7.5-month measurement period. Notice the different cut-sizes of
 214 the CPCs.

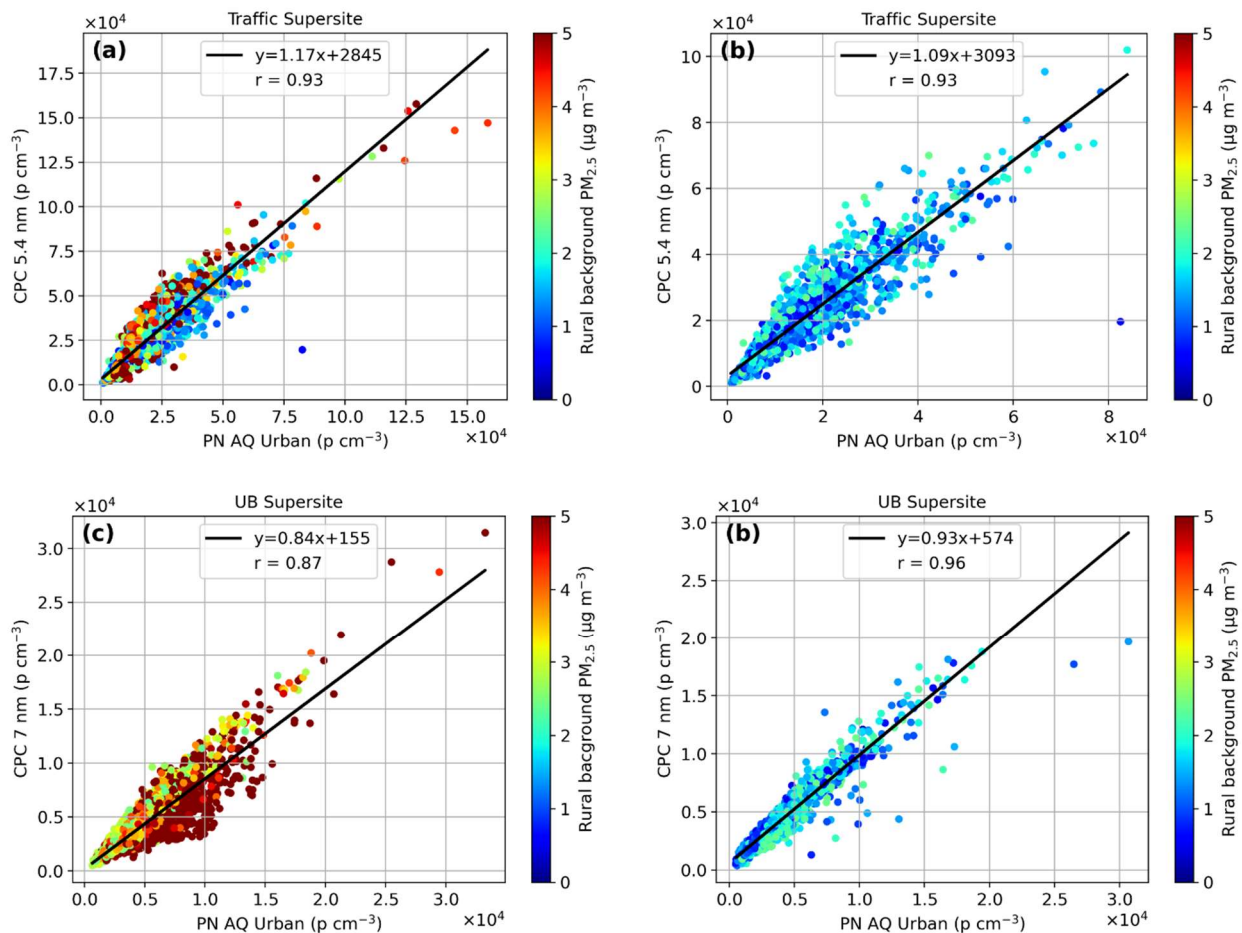
215 At the UB Supersite the difference in the measured PNC with the AQ Urban sensor and CPC is close to zero throughout
 216 the day. At the Traffic Supersite this difference is negative throughout the day, and the difference starts to increase when
 217 the morning rush hour starts as was observed at the Traffic Supersite also during the comparison period. The difference
 218 in the cut-off size of the CPCs at these two sites was only 1.6 nm so it probably cannot explain the markedly higher
 219 differences of the two instruments. The observed difference is likely connected to the different concentrations and particle
 220 size distributions between these sites. This idea is supported by the hourly-averaged particle number size distributions in
 221 Fig. S4 which show that at the Traffic Supersite the PNC for particles < 30 nm increase during the morning rush hour.
 222 The DMPS data below 10 nm is not available from the Traffic Supersite, but the shape of the size distributions indicates
 223 an increasing trend of PNC also below 10 nm size (Fig. S4a). On the other hand, the PNC shows decreasing trend during
 224 all hours at the UB Supersite for particles < 10 nm (Fig. S4b). The size distribution results suggest that particles < 10 nm
 225 do not considerably contribute at the UB Supersite. Hence, the much lower concentration of particles below 10 nm at the
 226 UB Supersite is probably the main reason for the better agreement between AQ Urban and the CPC in terms of average
 227 concentration.

228 The linear correlations of the measured PNC with the AQ Urban sensors and the CPCs at the Traffic Supersite and at the
 229 UB Supersite are shown in Fig. 6, where the data set was divided based on the median of the Rural background site PM_{2.5}
 230 concentration into two data sets; PM_{2.5} < 2.5 μg m⁻³ and PM_{2.5} > 2.5 μg m⁻³. The linear correlations of the measured
 231 PNC with the AQ Urban sensor containing the whole data set (not divided) are shown in Fig. S5. The slope of the linear
 232 regression was slightly higher (1.24, $r = 0.94$) compared to the whole data set (1.17, $r = 0.93$, Fig. S5) at the Traffic
 233 Supersite when PM_{2.5} concentration at the Rural background site site was elevated and lower (1.09, $r = 0.93$) when its
 234 concentration was low. At the UB Supersite the slope of the linear regression was same for the whole data set (0.83, $r =$
 235 0.89, Fig. S5) and for the data set where the low Rural background site PM_{2.5} points were discarded ($r = 0.86$). However,
 236 when discarding the data points with high PM_{2.5} concentration at the Rural background site, the slope increased from
 237 0.83 to 0.93 together with increasing correlation coefficient (r) which increased from 0.86 to 0.96. These results suggest

238 that the PNC measurement of the AQ Urban was affected by the regional background $PM_{2.5}$ concentrations. This idea is
 239 supported also by the colored scatter plots in Fig. S6 (and Figs. S5a and S5c), where the slope of this linear correlation
 240 seemed to be dependent on the $PM_{2.5}$ concentration measured at the Rural background site. The daily-averaged time
 241 series of $PM_{2.5}$ in Fig. S6 shows that the periods of elevated $PM_{2.5}$ concentrations are typically seen at all sites, indicating
 242 either regional or long-range transportation. During the winter BC concentration at the Rural background site increases
 243 simultaneously with the $PM_{2.5}$ concentration.

244 In Figs. S5b and 5d, the scatter plots, colored by the measured concentrations of NO_x at the same sites where the PNC
 245 were measured, are shown. At the Traffic Supersite higher PNC were measured together with high NO_x concentrations
 246 due to their common source (motor vehicle emissions, Fig. S5b). However, the linear correlation of PNC measured with
 247 the AQ Urban sensor and CPC was similar despite the varying NO_x concentrations at least at the Traffic Supersite (Fig.
 248 S5a).

249



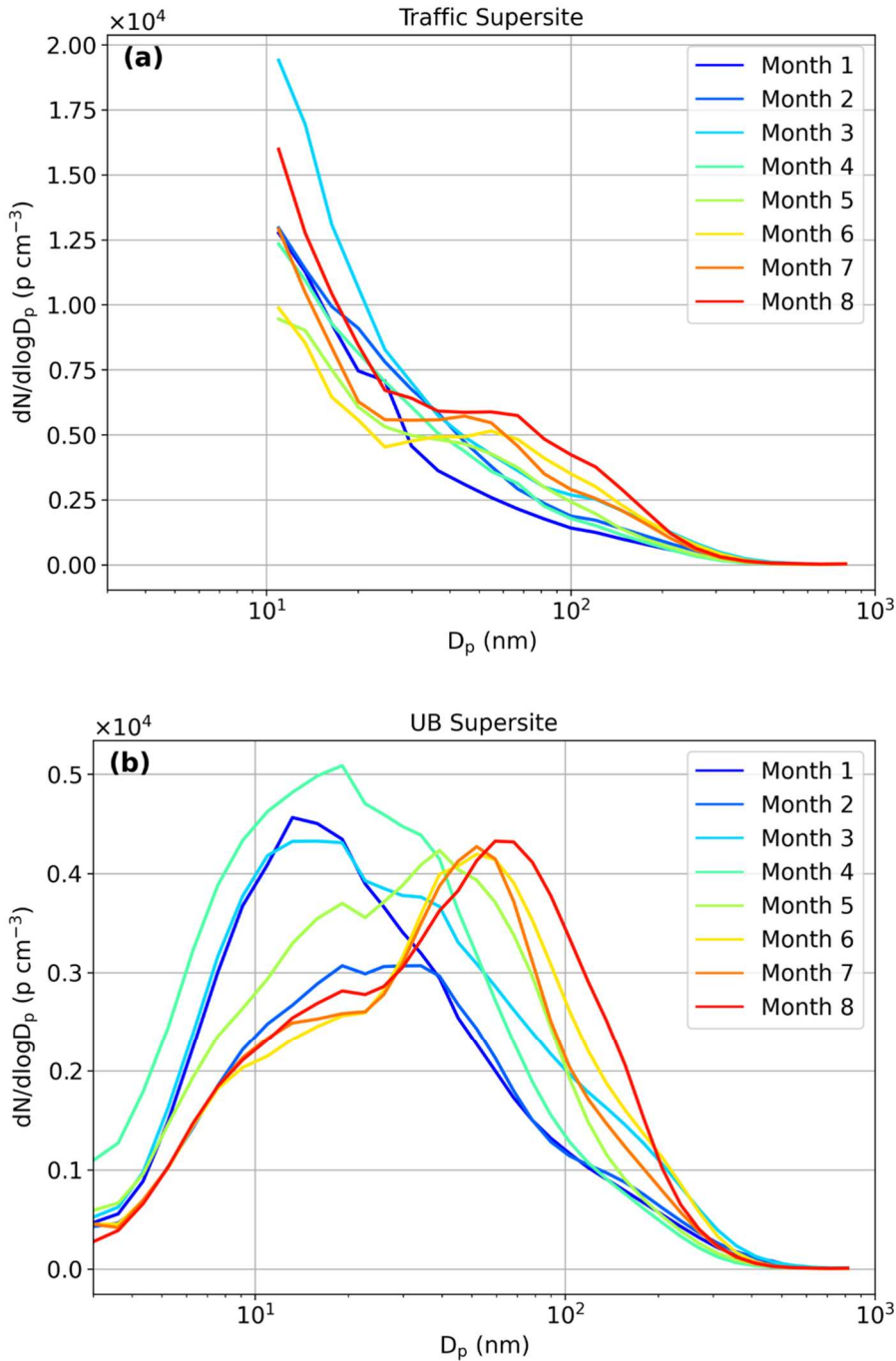
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251 **Figure 6.** Linear correlation of hourly-averaged particle number concentrations measured with the AQ Urban sensor and CPC at the
 252 Traffic Supersite and at the UB supersite during high (a and c) and low (b and d) $PM_{2.5}$ concentrations at the Rural background site
 253 during the 7.5-month measurement period. The color of the markers indicates $PM_{2.5}$ concentration at the Rural background site.

254 The results in Fig 6 and Fig. S5 show the agreement with the measured PNC between AQ Urban sensors and CPCs seem
 255 to be near unity when discarding the periods with regional or long-range transport (high $PM_{2.5}$ at the Rural background

256 site). The transported particles are aged and have larger sizes, and they mix externally with the traffic related ultrafine
257 particles forming bimodal particle size distribution, potentially affecting the performance of the AQ Urban. Interestingly,
258 however, the effect of increased regional $PM_{2.5}$ seems to be different at the Traffic Supersite (increased $PM_{2.5}$ increased
259 the slope) compared to the UB Supersite (increased $PM_{2.5}$ decreased the slope). The following paragraphs discuss the
260 effect of particle size distribution and $PM_{2.5}$ concentration on the measured PNC with AQ Urban sensor in more detail.

261 The monthly-averaged particle size distributions in Figs. 7a and 7b show that the size distributions shifted towards larger
262 particle size during the measurement period and the bimodal structure of the particle size distribution became clearer. The
263 mean particle size increased towards the summer months, which can be seen also when looking the daily-averaged time
264 series in Fig. S6, where the count median diameter from the AQ Urban sensor and the mean particle diameter calculated
265 from the DMPS data increased toward the summer months. Like the effect of $PM_{2.5}$ in Fig 6 and Fig S5, the increased
266 bimodality and mean particle diameter affected the ratio of the PNC measured with the CPCs and the AQ Urban sensors
267 (Fig. S6). However, the ratio between CPCs and AQ Urbans increased at the Traffic Supersite and decreased at the UB
268 Supersite. In general, it is not clear why the particle size increases during summer months. The possible reason may be
269 the growth of particles due to more favorable secondary aerosol formation via oxidation of organic matter from motor
270 vehicle exhaust during summer months (e.g. Ahlm et al., 2012; Gentner et al., 2017, 2012). During the summer months
271 the increased solar radiation, increased water content (Fig. S7) and increased concentrations of biogenic organic matter
272 may be another explanation for this growth (e.g. Srivastava et al., 2022).



273

274 **Figure 7.** Monthly-averaged particle number size distributions measured with DMPS at the Traffic Supersite (a) and at the UB Supersite
 275 (b) during the 7.5-month measurement period.

276 Results on the effects of regional $PM_{2.5}$ (Fig. 6 and Fig. S5) and the seasonality (Figs. 7 and S8) both suggest that the
 277 effect of bimodal particle size distribution on the performance of AQ Urban is different. This finding could be explained
 278 by the varying particle characteristics at these microenvironments. At the Traffic Supersite the PNC was constantly high
 279 due to the road traffic. During the regional and long-range transport periods the observed particle size distribution was
 280 not anymore unimodal due to the external mixing of traffic-related and regional and long-range transported particles. The
 281 AQ Urban sensor estimates the count median diameter using the assumption that the particle size distribution is unimodal.

282 Therefore, the increased regional background concentration causes an increase in the estimated count median diameter,
283 which reduces the conversion factor used to convert the electric current to PNC. The increased accumulation mode,
284 however, does not considerably affect the total PNC, which is still dominated by particles smaller than 20 nm (Fig. 7a).
285 Hence, even though the accumulation mode particles also affect the electric current measured by the AQ Urban, the
286 decreased conversion factor due to the increased estimated CMD, causes the sensor to underestimate the PNC at the
287 highly trafficked site.

288 At the UB Supersite the effect of traffic was low compared to traffic supersite, and the particle size distribution was
289 constantly concentrated on larger particle sizes (Fig. 7b). When particle size distribution was shifted to even larger particle
290 sizes (during summer or pollution transportation event) the AQ Urban sensor measures higher electric current. The
291 maximum limit of the estimated count median diameter of the AQ Urban sensor is ~100 nm but during the regional or
292 long-range transport periods, the size of the particles contributing the most to the measured electric current may be above
293 this limit, and so the AQ Urban sensor overestimates PNC.

294 In Figure S9, comparison of measured PNC distributions between AQ Urban sensor and CPCs having different cut-off
295 sizes are shown during the measurement period (Figs. S9 a and b) at both sites. At the UB Supersite where the CPC cut-
296 off size was 7 nm the measured PNC distributions between AQ Urban sensor and CPC showed good agreement. At the
297 Traffic Supersite there was clearly underestimation of PNC with AQ Urban sensor when particle concentrations were
298 higher, due to the higher fraction of ultrafine particles (below 10 nm) and due to the lower cut-off size of the used CPC.
299 It seems also that some overestimation of PNC was seen when concentrations were low. During low PNC concentrations,
300 the uncertainties related to bimodal size distribution could be more evident, explaining this result. Figures S9c and S9d
301 show the comparison of measured PNC distributions between AQ Urban sensor and the CPC having a cut-off size 10 nm
302 as well as comparison between the two CPCs with different cut-off sizes during the 6-week comparison period at the
303 Traffic Supersite.

304 Overall, the effect of bimodal size distribution on the AQ Urban measurement is important to consider when conducting
305 measurements in varying urban environments and geographic regions. As seen in the results, the performance of AQ
306 Urban in the PNC measurement was mainly very good in our measurements. However, the regional particle concentration,
307 thus, the accumulation mode of particles, was typically very low, which seemed to be especially suitable for the
308 performance of AQ Urban. It should be noted that the uncertainty caused by the bimodal size distribution could be much
309 more significant in locations where regional background concentrations are higher, like Central/Eastern Europe or India
310 (Sebastian et al., 2022; Trechera et al., 2023). Also, some particle sources, like residential wood combustion, can
311 considerably contribute to concentrations of particles larger than 100 nm (Harni et al., 2023; Kalkavouras et al., 2024)
312 potentially causing similar challenges as the increased regional background concentration. In general, it's, however, worth
313 noting that the measurement principle of AQ Urban is rather like other diffusion charger-based PNC sensors, like the
314 Partector 2 (Asbach et al., 2024). The challenge of bimodal size distribution has also been observed earlier when
315 considering the LDSA measurement of the diffusion charger-based sensors (Lepistö et al., 2024). Hence, it is justifiable
316 to think that the challenge related to bimodal size distribution could be relevant for other diffusion-charger based PNC
317 sensors as well.

318 Data Availability

319 Data available on request.

320 4 Conclusions

321 We investigated the possibility of using AQ Urban sensors in urban air quality monitoring to obtain PNC. The comparisons
322 were made at two different sites, at a heavily trafficked street canyon (Traffic Supersite) and at an urban background site
323 (UB Supersite) in 2022. First, the agreement between different AQ Urban units were investigated in two three-week
324 lasting campaigns (August 30th and October 10th, 2022) in the Traffic Supersite: the agreement with the measured particle
325 number concentrations within total of seven different AQ Urban sensors was good (Pearson r : 0.97–0.99, linear fit slopes:
326 1.0–1.06), showing that results with different AQ Urban units are well comparable in general. During this comparison
327 period, the PNC measured with a reference AQ Urban sensor were also compared to those measured with two CPCs
328 having cut-off sizes 5.4 and 10 nm. On average, the PNC measured with the AQ Urban sensor were slightly higher than
329 those measured with the CPC having a cut-off size 10 nm. The relative difference was, however, low compared to the
330 measured PNC. Also, the correlation between the reference AQ Urban sensor and the 5.4 nm and 10 nm CPCs were 0.98
331 and 0.97, respectively. These findings show that AQ Urban sensors should be well-suitable to measure the concentration
332 of particles approx. larger than 10 nm in highly trafficked areas.

333 The long-term agreement between AQ Urban sensors and CPCs was also investigated at the Traffic Supersite and UB
334 Supersite (January 1st and August 15th, 2022). Overall, the correlation between AQ Urban sensors and the CPCs was good
335 at both sites (r being 0.93 and 0.89, respectively), even though the cut-off sizes of the CPC at these two sites were different
336 (5.4 and 7 nm) compared to the lower limit of AQ Urban sensors (approx. 10 nm). The difference between AQ Urban
337 sensors and the CPCs increased especially during traffic rush hours at the Traffic Supersite. This result can, however, be
338 explained because of the increased emissions of particles smaller than 10 nm from traffic which are not detected with the
339 AQ Urban sensor. On the other hand, it was noted that especially long-range transported (LRT) pollution episodes as well
340 as time of the year can affect the accuracy of AQ Urban sensors. This result can be explained by the bi-modal particle size
341 number distributions observed especially during the LRT-episodes and summer, because AQ Urban sensor estimates the
342 count median diameter of particles assuming that the particle number size distribution is unimodal. Hence, the conversion
343 from the detected electric current into PNC cannot accurately estimate the size of the detected particles, causing
344 uncertainty in the measurement. Despite this downside of the method, it should be noted that the correlation between the
345 AQ Urban sensor and the CPCs was good during the whole measurement period, indicating that the sensor is well-suitable
346 for long-term particle number concentration monitoring in Helsinki.

347 Overall, the results show that AQ Urban sensor was well suitable to measure the number concentration of particles
348 approximately larger than 10 nm in two different urban environments in Helsinki, Finland. The result is interesting
349 regarding the EU's new air quality directive (2024) which requires particle number (> 10 nm) concentration monitoring
350 at pollution hotspots. The results show that diffusion charger-based measurement of PNC should be well-suitable for
351 urban air quality monitoring, enabling more-dense sensor monitoring network than CPC methodology. For example, the
352 sensors could be utilized to estimate potential hotspots for the measurements required by the directive. Still, it should be
353 noted that further validation of diffusion charger-based particle number measurements is needed. Even though the
354 challenges caused by bi-modal particle number size distributions in this study were rather minimal, it needs to be

355 considered that Finland has very clean air in terms of regional pollution (e.g., PM_{2.5}). Hence, the challenges caused by bi-
356 modal particle number size distribution could be much more significant in locations with higher regional pollution, i.e.,
357 higher accumulation mode of particles. Thus, further studies of the performance of diffusion charger-based particle
358 number sensors from different locations would be valuable for further conclusions.

359 Author contributions.

360 TL, JVN, TR, ES and HT participated the conceptualization; KT, TL, JVN, TR, ES and HT wrote the original manuscript
361 draft; KT, JVN, HP, AJ and PA participated the data curation; KT and JVN participated the data visualization; JVN, HP,
362 AJ and PA participated the investigation; JVN, HEM, TP, TR and HT participated the funding acquisition: All authors
363 participated in the interpretation of the results, manuscript review and editing.

364 Competing interests

365 The authors declare that they have no competing interests.

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